

# NUCLEAR PHENOMENA AND COSMIC RAYS

W. F. G. SWANN

Director, Bartol Research Foundation

## THE CHARACTERISTICS OF NUCLEAR ENTITIES

*Meaning of the Existence of the Particles:*—It is only a few years since physics hoped to correlate all the architecture of matter in terms of the ultimate properties of two entities, the electron and the proton. Now with a suddenness which is almost embarrassing, several other particles have been thrown into the arena and demand consideration in building the structure. Among the particles now available we have:

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| 1. The electron. | 6. The deuteron.                             |
| 2. The proton.   | 7. The hydrogen particle.                    |
| 3. The positron. | 8. The alpha particle.                       |
| 4. The neutron.  | 9. Nuclear entities of various kinds usually |
| 5. The photon.   | regarded as composed in some way             |
|                  | of more fundamental entities 1. to 4.        |

In cosmic-ray matters, at any rate, entities 1 to 5 form the main field of our interest, although the more complicated particles do enter into the discussion.

When we are presented with an array of entities such as those referred to, and raise with ourselves the question as to whether or not certain of them exist in the nucleus of some atom, we are apt to encounter ambiguities of meaning founded upon whether some complicated particle such as an alpha particle exists in the nucleus as an individual entity, or whether it is to be thought of as made up out of such things as protons and electrons. We are confronted, for example, with the question of whether the proton is to be regarded as a neutron plus a positron, or as an entity distinct in itself. In some atomic transmutations we may raise the question as to whether some of the particles which we observe were in the nucleus originally or whether they were formed in the process of its disruption. These uncertainties of meaning become enhanced when we try to picture a structure for the nucleus. In classical theory we became confronted with the problem of putting into a nucleus of certain limited size a number of entities whose classical dimensions were so great that they would have to

overlap in order to accommodate themselves. In wave mechanical theory the various entities appear dissolved in a kind of mathematical fluid, from which any one may be precipitated at any desired moment for inspection by a suitable reagent which takes the form of a mathematical operation. Under such conditions it may not be out of place to pause a moment, from time to time, for the purpose of deciding with ourselves what it is that we are talking about, and in particular as to what meaning is to be attached to the statement that a certain entity, let us say a proton, is, or is not, inside a nucleus; and, if in the nucleus, as to whether it exists there as a fundamental entity or as something which is to be thought of as made up of two entities—for example a neutron and a positron. To my mind, definiteness of statement can only be secured along such lines as the following: When we wish to introduce into our problem such an entity as an atom, that atom has a certain mathematical representative which is responsible for all of its activities in the theory. That representative may be a Hamiltonian function. This function figures in some differential equations which are representative of the theory of the subject. In these differential equations are certain co-ordinates which are potentially representative of all of the entities which may figure in the discussion of all that may occur.<sup>1</sup> Any particular solution of these equations represent a *state* of the system. Some of the co-ordinates representative of certain entities may be absent in *any particular solution*. If such is the case, the entities concerned are absent in the state representative of that solution. It may be possible in the case of some particular solution, representative of a state, to make a transformation of co-ordinates in such a manner as to reduce the number of the co-ordinates. Then, entities characterized by the new co-ordinates may be said to exist in the state concerned.<sup>2</sup> Thus, suppose among the fundamental entities we had neutrons and positrons, but not protons. Then a free proton, or a proton in an electric field, for example, is to be considered as a system which, primarily represented by a function of the co-ordinates of a neutron

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<sup>1</sup>The entities are supposed chosen so that they represent the minimum number necessary for telling the story of all that may occur through the agency of the accompanying mathematical theory.

<sup>2</sup>In this manner, for example, the co-ordinates of a suitable number of protons and electrons may, in certain cases, be mathematically welded into the much smaller number of co-ordinates of an alpha particle.

and a position, has been found, through a transformation of co-ordinates, to be represented by new co-ordinates to the extent of half the number. If, now, we raise the question of whether in an atom there are protons, or neutrons and positrons, the question at issue is whether the same transformation which reduced the number of co-ordinates in the single case of neutron and positron, above cited, will now function in similar manner to reduce the number of co-ordinates in the function representative of the state of the atom in question. If it does, we may say, by hypothesis, that a proton exists in the atom. It matters not whether some experiment reveals a proton as apparently ejected from the nucleus. The story of whether the said proton was, or was not, in the nucleus has no meaning except in the light of some definition; and the definition I have suggested seems to be the only obvious one available.

*Significance of the Existence of Different Atoms:*—While speaking of these rather general philosophical matters, one cannot resist the temptation to speculate a little further upon the significance of the quantum theory. At present we have a separate differential equation for each atom, the atom in question being characterized by the form of a certain function—the Hamiltonian function—entering into the equation. The different states of the atoms are characterized by the different solutions which are to be permitted as acceptable according to a certain criterion—the criterion of finiteness, single-valuedness, etc. May it not be that the different atoms themselves are to be regarded as representative of “quantum states” founded upon a yet wider idea of quantization. Many possibilities suggest themselves. Speaking generally, atoms of successively increasing atomic number are characterized, in part, mathematically, as systems of increasing numbers of co-ordinates. May it not be that there is one fundamental differential equation, or set thereof, involving, perhaps, in the initial instance an infinite number of co-ordinates, but of which only certain of the solutions satisfy the criteria demanded, finiteness, single-valuedness, etc., for example. It may be that all the solutions involving certain specified numbers of co-ordinates would be unacceptable. Presumably those involving more co-ordinates than are found in the heaviest known element would come into this category. The individual solutions in which the number of co-ordinates were limited would naturally satisfy, in addition

to the general differential equation involving the multitude of co-ordinates, certain special differential equations involving only the co-ordinates occurring in the solutions. Presumably these special differential equations would be those which we now think of as characteristic of the individual atoms.

*Similarity of Different Particles for High Energy:*—Another matter of significance concerns the respect in which the particles 1 to 9 really differ from one another. Of course the electron and positron differ from the neutron and photon in that they possess electric charge, and so have qualitative properties different from those of the uncharged entities. This is, however, only a special aspect of differences in properties such as one may think of as existing between the photon and the neutron, to which I shall presently refer. I wish for the moment to raise the questions involved in these particles in what we may call collision phenomena. The story of collision phenomena is governed, though not completely controlled, by two laws, conservation of energy, and conservation of momentum, which we may symbolize by considering a collision in which all the entities from (1) to (5), for example, are involved, and where, therefore, with subscript e for the electron, p for the positron, n for the neutron, P for the proton, and q for the photon, we may write

$$E_e + E_p + E_n + E_q + E_P = E'_e + E'_p + E'_n + E'_q + E'_P$$

where the dashed and undashed symbols refer to the conditions before and after the collision. Similarly, the conservation of momentum may be symbolized by the equation

$$M_e + M_p + M_n + M_q + M_P = M'_e + M'_p + M'_n + M'_q + M'_P$$

In these equations the various particles are characterized by the fact that, for particles (1) to (4) inclusive,

$$E = m_0 c^2 \left( \frac{1}{\sqrt{1 - \beta^2}} - 1 \right); \quad M = \frac{m_0 u}{\sqrt{1 - \beta^2}}$$

and for the photon,

$$E = h\nu; \quad M = h\nu/c$$

Here the material particles are characterized by a rest mass  $m_0$  and a velocity  $u$ , and the momentum of a particle is not expressible completely in terms of the energy. The quantum momentum is, however, completely expressible in terms of the corresponding energy, and indeed we may allow  $\nu$  to evaporate

from the picture and simply say that the momentum of the quantum is  $E/c$ . It is of interest, however, to extrapolate the situation to velocities comparable with that of light, for which case  $m_0$  is negligible compared to  $m$ . Thus, for example, in the case of an electron of a hundred million volts velocity,  $m_0$  forms only half a percent of  $m$ ; and, for such electrons and positrons as figure in the primary cosmic rays,  $m_0$  forms only one part in twenty thousand, or less, of  $m$ . For protons of  $10^{10}$  volts energy,  $m_0$  still amounts to 5% of  $m$ , but for  $10^{11}$  volts it forms only 0.5%. I wish to emphasize that at sufficiently high energies we may write for all of the particles, including the photons,  $M = E/c$ , and the equation of conservation of energy and momentum are completely summed up in two statements of the form

$$\Sigma E = \text{constant},$$

one vectorial, and the other scalar. All characteristics of the material particles and of the quantum have disappeared with the exception of the energy. A quantum and a proton of the same energy would behave in exactly the same way as regards what conservation of energy and momentum would have to say. Distinctions between the entities must now be sought on lines other than those having to do with conservation of energy and momentum. These distinctions commence to show themselves when we consider *experiments* to verify the predictions of the conservation of energy and momentum laws. Then the energy of the electron becomes something which is measured by a path deviation in a magnetic field, for example. The energy of a photon is something which is measured in a way which may be illustrated by the following example: Photons fall perpendicularly upon a hypothetical crystal grating. We confine our attention to those which come in some definite direction in relation to the grating. This direction defines for us the energy  $E$  to be assigned to the photon. You will see that I am thinking of the diffraction patterns produced by the photon; but I wish to suppress this idea in your minds, if you will permit me. I wish you to come upon it in another way. I wish to say that my measurement of the energy of the photon in terms of the angle of which I have spoken is, in the first instance, a matter of arbitrary definition; and, in the expression of the relation, an intermediate quantity  $\lambda = hc/E$  comes in, or rather a series of quantities  $hc/E$ ,  $2hc/E$ ,  $3hc/E$ , etc.

They come in abstractly in determining the various angles at which the rays coming off from the grating correspond to the same energy. They are, of course, the wave lengths  $\lambda$ ,  $2\lambda$ ,  $3\lambda$ , etc., which figure in that picture of the phenomenon which regards everything as represented by a train of waves, of wave length  $\lambda$ , and of corresponding frequency  $\nu = c/\lambda$ , incident upon the crystal. From our standpoint the wave picture is not to be regarded as any real thing, but more as an artificial mathematical substructure analogous to Fourier's analysis, and the frequency  $\nu$  is born of the primary concept of energy rather than the energy being born of the frequency  $\nu$ . Relegating frequency to this abstract role relieves us of those apparent difficulties which arise in our minds when we try to picture a quantum simultaneously as a particle and as a wave spreading throughout the universe.

Then again a difference between the kind of particles, quantum, electron, etc., makes its appearance when these particles act as perturbing influences upon some atom, or where their energies are deduced on the basis of some theory of their absorption in matter. In such cases, the electron, for example, becomes introduced as a perturbing agent productive of a field of the kind we may associate with a moving charged particle, whereas the photon is represented as a periodic disturbance. In such fields as these the maximum of distinction prevails between the photons and the charged particles and the neutrons, but it is a distinction inherent in, and depending for its meaning upon, the theory of the processes assumed.

The foregoing remarks have been made not so much with the object of drawing any constructive conclusions from them, as for the purpose of cementing what appears to be the logical attitude towards them in any problem which concerns their nature. One constructive feature, however, following from the condition which all of these particles attain when the energy is sufficiently high, is a feature following from the fact that the energy is in all cases proportional to the momentum. The feature in question involves that in a collision between two particles of the same or of different kinds, one of which is initially at rest, the velocity after collision is in the same direction as that before. Thus, if the particle  $a$  collides with particle  $b$ , initially at rest, resulting in a supposed change of direction of  $a$ , we have, from the momentum condition

$$E_a = E_a' \cos \theta_a + E_b' \cos \theta_b; E_a' \sin \theta_a + E_b' \sin \theta_b = 0$$

and from the energy condition

$$E_a = E_a' + E_b'$$

which demand for their consistency that  $\cos \theta_a$  and  $\cos \theta_b$  shall both be equal to unity. The feature is a very valuable one because it tells us that in the impact of very high energy cosmic rays with atoms so as to produce secondaries there is a perpetuation of the direction of the primary corpuscle so long as no energy goes into processes other than those involved in the laws of impact as specified.

### COSMIC RAYS

I must pass over introductory matters relating to the history of cosmic rays, methods of measurements, etc., and must take the matter up at the stage where we have to realize that a radiation of enormous penetrating power is entering our atmosphere. All the various particles which have been cited may be regarded as candidates for the position of cosmic rays. However, their credentials are different. Heavy charged particles such as alpha rays face the difficulty that all theories lead us to expect a very high absorption of such particles in the atmosphere, unless they possess an energy so high that their rest mass is negligible compared with their total mass. When this condition is satisfied, their rate of loss of energy by ionization alone depends only upon their energy and upon the square of the nuclear charge.<sup>3</sup> However, the energy which such a thing as an alpha particle must attain in order that its rest mass shall be as unimportant as that of an electron of the same energy is about 8,000 times the magnitude of that electron's energy. For such reasons alpha particles and heavy nuclei have not featured to any considerable extent as candidates for the position of primary cosmic rays, however great a part they may play in the subsequent activity, initiated in the first instance by the primary rays, and leading to atmospheric conductivity. However, such things as alpha particles, and particularly protons, are considered by more than one investigator as presenting reasonable credentials for consideration as primary cosmic-ray particles.

<sup>3</sup>I must here utter a word of warning based upon the fact that the crowding of the lines of electric force towards the equatorial plane perpendicular to the motion is a phenomenon depending upon the velocity rather than the energy. This phenomenon plays no ultimate part except when radiation reaction is considered. But, if it should play a part, then, to that extent, high energy particles of the same charge and energy would not be equivalent, regardless of their rest masses.

It is of course to be understood that practically all of the phenomena by which we observe cosmic rays are produced by secondaries. The cloud expansion chamber shows us an ample occurrence of phenomena in which relatively soft rays of only a few million volts velocity make their appearance, from some matter in the vicinity, sometimes in large groups, and obviously as the result of the initiation of some act by the primary rays. Occasionally from a mass of lead, for example, there will spring out bursts of rays, as many as five thousand in number. These rays do not appear to emanate from one point, but from several centers. Dr. G. L. Locher, at our laboratory, has given evidence for supposing that the primary center, where the burst initiates, emits neutrons among other things and that these neutrons serve as secondary initiators of the disruption of other atoms, so that the whole phenomenon spreads through the material, or throughout a portion of it, and so results in the very large bursts which are observed. We are at present conducting experiments along other lines and have a certain amount of evidence to show that bursts in one piece of matter can initiate bursts in others. This evidence is contained in an experiment carried out by Dr. and Mrs. C. G. Montgomery and myself. In this experiment we measured the bursts produced in the walls of an iron sphere which was suspended below a large tank of water so that the amount of water could be varied. It was found that the frequency of the bursts increased with the thickness of the water and then diminished with further increase. The increase of burst-production with increase of water is attributed to the stimulation of bursts in the iron sphere by the bursts produced in the water. The further diminution of bursts with increased thickness of water is attributed to a compensating action resulting from the absorption of the primary radiation by the water. The actual experiments showed an increase of 20% in the frequency of the bursts corresponding to  $0.5 \times 10^6$  ions, for a water thickness of 79 cms. To remove the possibility that the apparent increase of number of bursts in the sphere represented simply a measurement of spurts of ions produced in the sphere by rays which had come directly from the water, the iron sphere was replaced by a magnesium sphere, and the experiments were repeated. Any effect produced by the direct action of the rays from the water, without intermediary action in the walls of the sphere, should show itself just as well for the magnesium sphere as



for the iron. However, no increase in burst frequency was found by increasing the thickness of the water when the magnesium sphere was used.

The fundamental significance of this experiment is that it substantiates the opinion expressed by Dr. Locher to the effect that a number of atoms participate in the production of the bursts. This gives us some relief from the difficulty inherent in the fact that the total energy required to produce some of these bursts is greater than the energy which could be reasonably expected to be liberated in one act in any atomic process which we know of, including the complete annihilation of heavy atoms. It also weakens considerably the claims of a rival theory which has been put forward to account for the origin of these bursts, and which, in view of its dramatic nature, I must not pass by without mentioning. Recent developments in atomic structure and the theories thereof have come to a realization of the possibility of the disappearance of matter and the accompanying appearance of radiant energy in proportional amount. They have also envisioned the reverse process in which radiant energy can be converted into material substance. The general idea of the production of these bursts inherent in the theory to which I have referred is to the effect that radiant energy in the form of a photon cosmic ray descends upon the substance under test. Occasionally such a ray comes into violent contact with the nucleus of an atom. Under these conditions it is supposed that nothing in particular happens to the atomic nucleus, but that the photon becomes mathematically irritated in such a manner as to cause it to decide to change its existence, commit suicide, and become resurrected as a group of particles. If you should ask for a crude analogy, I suggest that you think of a spiritualistic seance. The photon is the ghost, the shower of particles is the materialized ghost, and the atom is the medium.

There is sometimes even an indication of a delay between the different portions of an atomic burst. Fig. 1 shows a galvanometric trace on moving photographic paper showing a burst at the point marked by the arrow. The burst is recorded as ionization in a closed chamber; but, as a check, a system of counters was distributed about the chamber so as to record these bursts by other means. The sharp lines indicate the discharge of the counters and it is obvious that we have here two discharges separated by a distance of what amounts to about

one second, and which seem closely associated with the complete bursts as recorded by the galvanometer. It is perhaps too early in view of the limited number of such cases to say that we have here an illustration of induced radioactivity brought about by cosmic rays, but the result indicated is at least significant, particularly when it is remembered that, with the arrangement of tubes used the chance of two random discharges coming as close together as these is negligible.

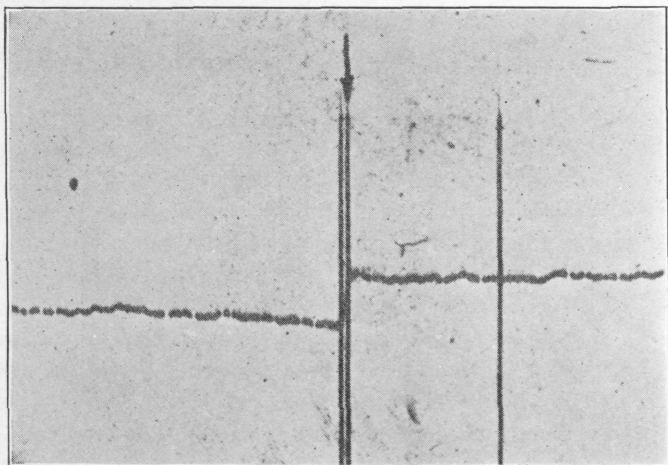


FIGURE 1

*The Exponential Law of Absorption.*—It has, of course, been known for many years that what is now called the cosmic-ray intensity varies with altitude in a manner which is approximately described by the supposition that the radiation is absorbed according to an exponential law. Now the hypothesis that the primaries are composed of photons of definite frequency lends itself reasonably readily to the explanation of such a law. The characteristic possessed by photons which is of significance in this connection is that of passing through matter without the continual loss of energy in small amounts, the energy losses being confined to amounts comparable with the whole energy of the photon, but taking place only rarely. Under such conditions the intensity of the radiation is governed by the laws of chance in relation to the distance travelled, just as chance determines the density of a stream of bullets at different distances from a machine gun, when the machine gun is fired

into a forest. On the other hand, charged particles, at any rate those of energies comparable with those met in former investigations, lose energy continually in passing through the air, the individual energy losses amounting to insignificant fractions of the total energy of the ray concerned. Under such conditions the rays have a definite range. A parallel beam of rays suffers no change of intensity as measured by the density of the rays until the distance is reached at which its intensity falls to zero. Thus, at first glance, at any rate, the hypothesis of charged corpuscles is entirely unsuited to the explanation of the exponential law of absorption. Until comparatively recently, moreover, the hypothesis of charged particles was ruled out on the basis of the effects which they would imply as the result of the action upon them of the earth's magnetic field.

*Evidence of Charged Particle Primaries:*—The earth's magnetic field is a very potent agent in controlling the activities of charged particles which seek to approach our earth. The earth's field is weak but its extent is great, so that at the equator an electron must have from one to six times ten thousand million volts energy depending upon the direction in order to reach the equator. The energy necessary for entering becomes less and less as we proceed toward the poles. The orbits of the electrons assume extraordinarily complicated forms. The smaller the energies of the rays, the more easily are the paths bent. Many years ago, the Norwegian physicist, Carl Störmer, suggested that the Aurora Borealis might be caused by electrons emitted in this case with great energy from the sun. The effect of the earth's magnetic field upon these electrons would be to cause them to move toward the polar regions. The smaller the energy, the more would be the bending of the electrons' paths in such manner as to cause them to enter the atmosphere near the poles; and, even to get the aurora to exhibit itself, on such a theory, at latitudes as low as that at which it is found, Störmer found it necessary to attribute to the electron energies a thousand times greater than any which had been encountered in the laboratory at that time. In those days such an assumption was regarded as very speculative. The mathematics of this subject is contained in its essential elements in the work of Störmer, done some twenty years ago. However, the subject has received a renewed interest in the light of modern developments in connection with cosmic rays. It has been convenient to consider certain specific matters

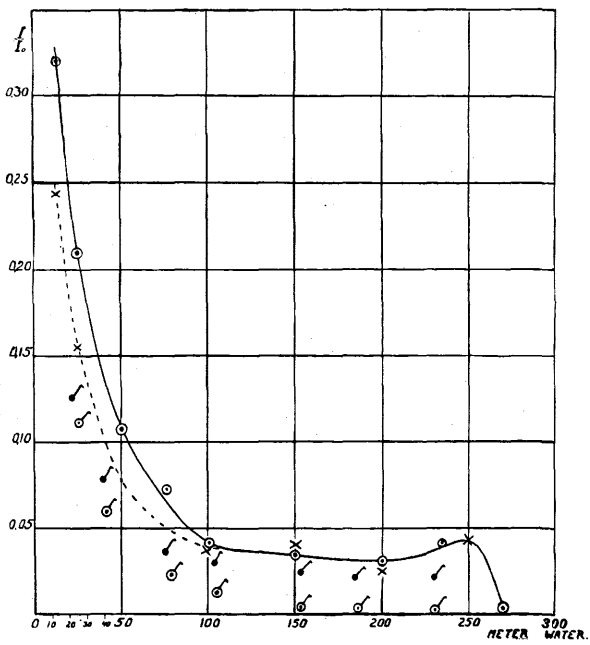
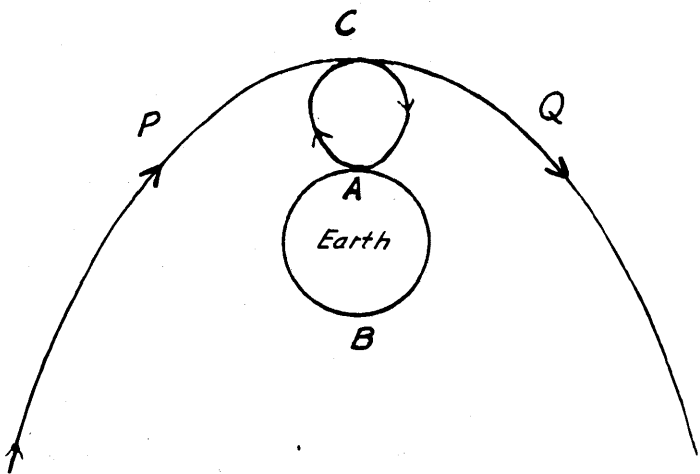


FIGURE 2 (Upper)

FIGURE 3 (Lower)

sometimes as generalizations of, sometimes as special cases of Störmer's theory, and sometimes by special calculations made *ab initio*, with the immediate end in view. Ten years ago, I showed by calculation that an electron with an energy so large that a thousand million volts would be necessary to give it that energy, would not be able to approach the earth in its equatorial plane nearer than to eight times the earth's radius, without being turned back into space. To reach the earth's surface at the equator, an electron must have an energy at least equivalent of that attained under a potential difference of ten thousand million volts. Even under these conditions, as I pointed out about three years ago, the electron which just succeeds in reaching the earth at the point A, Fig. 2, travelling in the magnetic equatorial plane, does so by describing a complete loop. It is easy to see why the electron describes such a loop. You might think that an electron coming from the lower half of the diagram and approaching the earth, would try to reach it at some point such as B. However, as the electron approaches the earth, the earth's magnetic field demands that the path of the electron shall bend, and continue to bend. In order to be able to obey the earth's magnetic field and yet reach the earth, the electron describes the orbit PCAQ shown in Fig. 2. By looping the loop completely, it is able to secure the maximum amount of bending in obedience to the earth's magnetic field, and indeed actually makes use of this bending to come back and touch the surface of the earth before it returns to space.

Now my purpose in showing Fig. 2, is to call to your attention the complicated nature of the orbits of electrons approaching the earth. Störmer spent very many years in calculating these orbits; and, indeed, they can not be calculated by elementary processes of mathematical procedure. Many of them twist about and curve all over the place in most fantastic manner. Under these conditions one might suppose that if an appreciable fraction of the primary cosmic rays was composed of electrons, there would be a very great variation of cosmic-ray intensity with latitude, in view of the fact that it is easier for the electrons to get in at the poles than at the equator. Since until recent times no such variation with latitude was known, it was customary to assume that no appreciable fraction of the primary rays could consist of charged particles. Then three or four years ago, J. Clay in Europe and A. H. Compton and his

associates, in a world survey, found a definite variation with latitude, but of a rather peculiar nature. For latitudes north or south of  $34^\circ$ , there was very little variation. For latitudes lower than  $34^\circ$ , there was a diminution in cosmic-ray intensity which amounted to 14% of the equatorial value at sea level, and to as much as 33% at an altitude of 4,300 meters. Such a condition was at first very difficult to understand. Then it was shown by Lemaitre and Vallarta that if a certain mathematical theorem concerned with the motion of the electrons in the earth's magnetic field could be regarded as true, the story of the cosmic-ray intensity, although extremely complicated in the actual details concerned with the orbits of the electrons themselves, should show remarkable features of simplicity as regards the intensity itself. It turned out that if the theorem to which I have referred was true and if the cosmic rays were uniformly distributed in direction in outer space, then, while their paths would be enormously distorted as they approached the earth, they would be distorted relatively to each other so that the number of rays coming through a cosmic-ray telescope pointed in any direction would have the following characteristics. At any assigned place, and for any one energy of ray, *either* the number would be exactly the same as it would have been had there been no magnetic field, in spite of the fact that the direction of these rays, if produced backwards outside of the earth's atmosphere to remote distances would there have nothing like the directions which they would have had in the absence of the earth's magnetic field, *or* the number would be zero. There could be no compromise. Either the electrons came in with the normal intensity or they did not come in at all. The truth of the mathematical theorem to which I have referred was first sensed by Lemaitre and Vallarta. It was found subsequently to involve principles rather more subtle than had first been supposed, but later by a more rigorous mathematical treatment of the subject I was able to establish the truth of the theorem in a manner which I believe is regarded as satisfactory even by those who have doubts concerning the complete story of the Lemaitre-Vallarta theory itself. The significant elements of the Lemaitre-Vallarta theory may be illustrated in the following way. Suppose that we confine our attention to electrons of any one energy, and, let us say, of positive sign. Then, in general, if we should take our stand at any

particular latitude on the surface of the earth, there would be, for any assigned electron energy, a certain cone with its axis of symmetry tangential to the earth and pointing due west. Within this cone no rays of the assigned energy would enter. Outside of it, the rays would enter with the normal intensity. As we moved towards the pole, the cone would become narrower in angle; and, at some latitude sufficiently high, would become so narrow as to close up completely, so that, at this latitude, there would be no direction from which rays of the assigned energy could not enter, and the same may be said for all higher latitudes. Going back to our starting point, however, and moving towards the equator the cone would widen up in angle so that the direction from which rays could not approach would comprise more and more of the sky. If the assigned energy of the electrons were sufficiently small, the cone would widen up to such an extent as to turn inside out and cover the whole of the sky. Under these conditions no rays of the energy concerned would reach the point in question from any direction whatsoever. On the other hand, if the energy were sufficiently high, the cone of exclusion would narrow down to a small angle, even to zero angle at the equator itself, so that here and everywhere else on the earth, rays of this energy would enter from all directions.

This story of the cone contains the story of the variation of the total cosmic-ray intensity with latitude, and it also contains the story of the difference between the intensity from the east and from the west for any given latitude. If all the rays had one single energy and all carried the same sign of charge, say positive, the story of the difference between the intensity from the east and from the west would be very simple. If we were at a place where the cone of exclusion existed at all, there would be no intensity from the west and the full intensity from the east. In general, this story is complicated by the existence of a wide range of energies for some of which there is an exclusion angle and for some of which there is not. It is also complicated by the possibility of there being charged particles of both signs. It is obvious that if charged particles of both signs existed in equal amounts there would be no difference in intensity from the east and from the west, although there would, of course, be a reduction in each of these intensities. The whole story of these latitude and directional effects is rather complicated, and I must not enter into it in detail. It

must suffice to summarize the main facts.<sup>4</sup> By experiments carried out by T. H. Johnson and J. C. Street on the top of Mount Washington in the summer of 1932, the existence of an east-west asymmetry was verified and the observations were such as to indicate that the charged particles responsible for the effect were charged, preponderatingly, positively. These results were confirmed and extended by the work of T. H. Johnson, and independently by that of L. W. Alvarez and A. H. Compton in Mexico. Since that time Johnson has extended the observations to a wide range of altitudes and to equatorial latitudes. Combining the results of the experiments on the latitude- and directional-effects, we may then conclude as follows:

(1) The latitude intensity measurements of A. H. Compton and his associates give, from the sea level measurements, a diminution of 12 per cent<sup>5</sup> of the cosmic ray intensity in passing from high latitudes to the equator. For measurements at high altitudes, the corresponding change is 25 per cent.<sup>6</sup>

(2) The radiation of corpuscular nature which carries a positive charge is in excess of that carrying a negative charge.

(3) By combining the latitude variation in intensity, which depends upon the sum of the negative and positive corpuscular currents, with data on asymmetry, which are determined by the difference between these currents, T. H. Johnson is able to determine how much of each sign of current is involved. Confining attention to the sea level data on the latitude effect,

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<sup>4</sup>For those who are unacquainted with the subject it must be remarked that relative intensities in different directions are obtained by an appliance which we may call a cosmic-ray telescope. A Geiger-Mueller counter comprises a hollow metal cylinder with a wire passing along the axis, the whole device being enclosed in glass and containing gas at reduced pressure. If the potential difference between the wire and the cylinder is adjusted to the right amount, the passage of a cosmic ray through the cylinder precipitates a discharge which may be amplified and recorded by suitable means. Suppose that three of these counters are arranged with their axes parallel and their centers on a line perpendicular to the axes, and suppose that the amplifying and recording mechanism is such that the final record is made only if all the counters discharge at once, then it is obvious that the system constitutes a cosmic-ray telescope which measures only those rays which come in such directions as to cause them to pass through all three cylinders.

<sup>5</sup>The 14 per cent quoted by Compton is expressed in terms of the intensity at the equator. A similar remark applies in the case of the 25 per cent cited later, which corresponds to Compton's 35 per cent of the equatorial intensity.

<sup>6</sup>It must be remarked that this 25 per cent and the 12 per cent cited above do not constitute a discrepancy. Both are lower limits, and the high altitude data give the larger value because they are more sensitive to the corpuscular nature of the rays, since they involve lower energy rays which have not been absorbed or had their potency for measurement reduced by the lower regions of the atmosphere.



it results that practically all of the corpuscular radiation which corresponds to energies sufficiently low to show a directional effect is of the positive type. While this result is not as inevitable when based solely upon the less accurate high altitude data for the latitude effect, it is in agreement with those data within the limits of their accuracy.

(4) The latitude effect gives us a lower limit for the amount of the corpuscular radiation. However, the limit obtained in this way does not include any corpuscular radiation of such an energy as can reach the earth at the magnetic equator. On the other hand the existence of an asymmetry at the equator enables one to add to the lower limit an additional corpuscular current. The net result is still only a lower limit, because it does not include any corpuscular current of energy so high that it would show no asymmetry effect at the equator. Proceeding according to these principles, and expressing percentages in terms of the total radiation of all kinds as measured at high latitudes, T. H. Johnson has been able to add 4.5 per cent to the 12 per cent resulting from A. H. Compton's latitude measurements at sea level. This would lead us to conclude from the sea level observations alone that at least 16 per cent of the intensity as measured at high latitudes is of the charged corpuscular nature. However, if we confine measurements to those at high altitudes, Dr. Johnson finds that the equatorial asymmetry data demand a minimum contribution of 6 per cent to the high latitude, high altitude intensity; and A. H. Compton's latitude measurements give a contribution of at least 25 per cent, so that these high altitude measurements demand a total contribution of 31 per cent as the minimum charged corpuscular contribution to the radiation.

The 31 per cent demanded for the corpuscular contribution is sufficient to "spoil" the exponential law provided so readily by the photon hypothesis unless the corpuscular hypothesis can itself be adapted to give that law. With the necessity of this adaptation facing us, it then naturally becomes of interest to see how far we can account for all of the cosmic-ray phenomena on the hypothesis that the primaries are of a corpuscular nature.

*Difficulties Involved in Corpuscular Hypothesis:*—According to the most naive views, the exponential law would have to be provided for in the corpuscular theory by the existence of a wide range of incoming corpuscular energies which penetrated

the atmosphere to different depths depending upon the energies of the individual rays concerned. The amount of radiation to be found at any depth below the top of the atmosphere would depend upon the number of incoming particles which happened to exist in the energy ranges necessary to reach the depth concerned; and the existence of an exponential law of absorption, or, if you prefer, of intensity with distance traversed, would necessitate the assumption of a special type of energy distribution in the incoming particles necessary to secure that law. Even though we accept the necessary assumptions, however, a great difficulty remains. For under the simple conditions postulated it would turn out that the quality of the radiation would be the same at all altitudes. By this I mean that if at sea level, for example, we should find a certain distribution of energy among the rays, then at higher altitudes one would find the same relative distribution. The number of rays having any given energy would be greater at the higher altitude; but rays of all energies would be greater in the same proportion. At first sight this result is contrary to our intuitions and is contrary to what has presumably been generally believed; for it is natural to argue that the rays at high altitude would contain a preponderatingly larger proportion of low-energy rays than would those at low altitudes, because the low-energy rays cannot penetrate to low altitudes. We must remember, however, that the rays which possessed high energy at high altitudes will, by process of absorption, become rays of low energy at low altitudes. They exist at low altitudes not because of the energy which they *have* there, but because of the energy which they *had* before they got there. If all of these matters are taken into account, then, as I have shown elsewhere, providing that one assumes the distribution of energies in outer space necessary to give the exponential law, it follows, as an inevitable consequence, that the quality must be the same at all altitudes.

Now the experimental data at our command resist, absolutely, harmonization with the view which concludes that the quality shall be independent of the altitude; for, upon such a view, the number of atomic bursts from lead, for example, would increase with altitude exactly in proportion to the measured number of cosmic rays themselves. Now such a conclusion is drastically contrary to some recent experiments of C. G. and D. D. Montgomery upon the frequency of these

bursts at high altitudes. For the Montgomeries have found that whereas the cosmic-ray intensity increases by a factor of five from sea level to the summit of Pike's Peak, the frequency of the atomic bursts increases by a factor of twenty-five. Similar results have been found by R. D. Bennett, G. S. Brown and H. A. Rahmel. Further, analogous conclusions follow from the experiments of T. H. Johnson and of B. Rossi and S. de Benedetti, upon small showers of secondary cosmic-rays produced by the primary cosmic radiation. Again recent measurements carried out in stratosphere flights<sup>7</sup> with Geiger counter apparatus designed by G. L. Locher and myself, when combined with data on the increase of intensity with altitude as measured by ionization chambers, have shown that the ionization produced by the rays in a closed vessel increases more rapidly with altitude than does the intensity of the rays itself, indicating once more a change of quality with altitude.

*A New Form of Corpuscular Theory:*—In order to overcome these difficulties, and at the same time secure the exponential law in what seems to be a more natural way, I have been led to formulate a view as to the mechanisms of the processes involved which, in its simplest aspect, and to a first approximation, takes the following form. Let us suppose that primary rays of a single energy enter the atmosphere uniformly in all directions and that, as they travel through the atmosphere, they produce along their paths secondary rays possessing energies such as those which figure in cosmic-ray phenomena, but smaller than the energy of a primary ray. The secondary rays may be produced directly, or through a photon as intermediary. Let us suppose that these secondary rays are the chief entities which are observed in our cosmic-ray counters, and that they perpetuate the direction of the primaries which produce them. This last-named characteristic is hardly an assumption since it follows, as I have already shown, from the laws of impact in which both the primary and secondary particles have very high energies. In addition to this we shall assume, and this is the vital assumption, that the loss of energy per cm of path is proportional to the energy of the primary ray. Or, in other words, we shall assume that the number of secondaries per

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<sup>7</sup>The first of these flights was made by Major W. E. Kepner, Capt. A. W. Stevens and Capt. O. A. Anderson. The second was made last fall by Prof. and Mrs. Jean Piccard.

cm of path is proportional to the energy of the primary. It is then clear that, even though all the primaries come right through the atmosphere so that the number of them passing through a square centimeter is the same at all altitudes, the measured effect, depending as it does upon the number of secondaries, will increase with altitude because of the increase of primary energy with altitude. When we submit the matter to calculation we find that the intensity as measured by the number of rays follows exactly that law which we have called the exponential law.

For, if the number of secondary rays produced per centimeter of path of the primary is proportional to the energy of the primary, then, if the secondaries perpetuate the paths of the primaries, the number of secondaries  $n_\theta$  per unit area per unit solid angle corresponding to any zenith angle  $\theta$  is

$$n_\theta = aE \quad (1)$$

where  $E$  is the primary energy and  $a$  is a constant.

If the primaries lose energy entirely by the creation of secondaries, and if  $dx$  is an element of path of the primaries, and  $\beta$  a constant,

$$-\frac{dE}{dx} = \beta n_\theta = \beta aE \quad (2)$$

So that

$$E = E_0 e^{-\beta ax} \quad (3)$$

Moreover, in view of (1)

$$n_\theta = (n_\theta)_0 e^{-\beta ax} \quad (4)$$

Again, (3) and (4) show that the apparent coefficient of absorption of the rays is independent of their energy, so that, without disturbing the exponential law, it is possible to permit the primary rays to possess a wide range of energies, and thus to remove one of the postulates which, at first sight, it might seem necessary to make. All energies give, in fact, an exponential law with the same coefficient of absorption.

The main feature of the foregoing theory is that, in it, the exponential law of absorption is secured as the result of the mechanisms of the processes taking place in the atoms, the emission of secondaries, and does not rely upon some peculiar distributions of energies among the incoming rays. Again, having secured now a variation of quality with altitude, we are well prepared to see in a natural way how such experiments as

those of the Montgomeries can be accounted for. Thus while we suppose that the law of production of secondary rays from the *air* is one which makes the number produced under assigned conditions proportional to the energy of the primary rays, let us suppose that in the case of *lead*, the rate of production of those secondaries which we call cosmic-ray bursts is proportional to a higher power of the energy than the first. Suppose, for example, that doubling the energy of the primary rays gives us four times the number of bursts. Then it is easy to see that, as in the case of the experiments of the Montgomeries, if the measured cosmic-ray intensity increases by a factor of five from sea level to the top of Pike's Peak, the number of bursts will increase by a factor of twenty-five. Moreover, in a more detailed form of the theory, we may well expect that the nature of the secondary rays produced from air will depend to some extent upon the energies of the primaries. In fact, the secondaries themselves may, in certain cases, arise not directly from the primaries but through the intermediacy of photons produced by the primaries, which photons in turn eject the electrons as secondaries from the atoms of air. There is thus ample provision for the situation found in which the ionization in a closed vessel varies with altitude in a manner different from that for the intensity of rays as measured by counters, since the ionization is produced by the secondaries and even by other entities, as neutrons, etc., which may be liberated by the primaries.

It will be observed that the foregoing simple theory makes the coefficient of absorption of the energy the same as that of the measured intensity, when the intensity is measured by the numbers of the secondary rays. This fact is of interest because it suggests between the energies of the rays entering the atmosphere and the energies as measured at sea level, a relation calculable in terms of the relation between the cosmic-ray intensity at, or near, the top of the atmosphere and the corresponding intensity at sea level. The recent stratosphere flight made by Major W. E. Kepner, Capt. A. W. Stevens, and Capt. O. A. Anderson, and also that made by Professor and Mrs. Jean Piccard, both with Geiger counter apparatus designed by G. L. Locher and the writer, agree in showing that the vertical intensity, when extrapolated to the top of the atmosphere, is about 90 times the sea level value. The minimum electron energy necessary to permit vertical entry

in opposition to the earth's magnetic field in these latitudes, is about  $4.5 \times 10^9$  volts. The corresponding sea level value would consequently be about  $5 \times 10^7$  volts. This is a reasonable value in the light of the requirements demanded of it. The energy necessary for vertical entry at the equator is about  $3 \times 10^{10}$  volts, and if we could assume the same law of increase of intensity with altitude at the equator as at these higher latitudes, the corresponding minimum sea level energy for the primaries would be about  $3 \times 10^8$  volts. Of course, these are only *minimum* values for the energies of the vertical rays, and higher energies at entrance will correspond to higher sea level energies. Apart from any other considerations, however, the principle here exemplified is sufficient to explain why cloud chamber experiments made, of course, at low altitudes, have failed to reveal corpuscular energies as great as those which would be suggested by consideration of the requirements of the earth's magnetic field. Moreover, consideration of these matters serves to emphasize the importance of cloud chamber energy measurements at high altitudes.

An element of difficulty exists from a consideration of the case of rays which are inclined appreciably to the vertical, and which at entry are of sufficiently low energy to show azimuthal asymmetry. These rays, traveling as they do through distances in the atmosphere considerably greater than the vertical rays, would be expected to become reduced in energy at sea level to values below those permissible for the performance of their functions. This difficulty tends to disappear in a more complete formulation of the theory to which brief reference will now be made.

*Extension of the Theory:*—While the foregoing simple form of theory correlates the more immediately obvious phenomena, it requires modification in detail. That very feature which gives the power to predict an exponential law—the feature which causes the percentage rate of absorption of energy to be independent of the energy—is one which, in its exact form, denies a fact characteristic of the azimuthal asymmetry effect, the fact that the percentage asymmetry increases with altitude. For this increase with altitude means that the primary rays which are responsible for the asymmetry, and which are therefore the rays of least energy, have a greater apparent coefficient of absorption than that which corresponds to the average radiation. In other words we must admit an increase of absorbability with

decrease of energy. Such a provision may be made purely empirically. Thus, if (1) be modified to the form

$$n_{\theta} = \alpha E^{1-\lambda} \quad (5)$$

where  $\lambda$  is a constant, (2) assumes the form

$$-\frac{dE}{dx} = \beta \alpha E^{1-\lambda}$$

and, if we define the coefficient,  $\mu_e$  of absorption of the energy at any point as  $-(1/E) (dE/dx)$ , we find

$$\mu_e = \beta \alpha E^{-\lambda}$$

We are concerned more particularly with the measured coefficient of absorption  $\mu_n$ , defined as  $-(1/n_{\theta}) (dn_{\theta}/dx)$ . In view of (5)

$$\mu_n = (1-\lambda) \mu_e$$

so that on the basis of the hypothesis under consideration, both  $\mu_n$  and  $\mu_e$  increase with decrease of energy.

The result may be secured in another way, having a more direct physical significance. For if, leaving (1) unchanged, we replace (2) by

$$-\frac{dE}{dx} = \beta n_{\theta} + \gamma \quad (6)$$

the quantity  $\gamma$  represents a constant loss of energy per centimeter of path all along the path of the primary. It is symbolized, for example, by such a loss as is represented by ordinary ionization.

Combining (1) and (6) we thus obtain

$$\mu_e = \beta \alpha + \gamma/E \quad (7)$$

and observing from (1) that  $\mu_n = \mu_e$ , we have

$$\mu_n = \beta \alpha + \gamma/E$$

which again gives an expression which causes  $\mu_n$  to increase with decrease of  $E$ .

It is of interest to observe in general that if (1) be modified to

$$N_{\theta} = \alpha E^s \quad (8)$$

$$\mu_n = s \mu_e$$

so that if  $s$  is greater than unity,  $\mu_n$  is greater than  $\mu_e$ . Such a provision has an advantage in causing the ratio of the energy

of the rays entering the atmosphere to the energy of the rays at sea level to be less than the ratio of the corresponding measured cosmic-ray intensities. This consequence lessens the difficulties already referred to in the matter of the asymmetric rays, concerning the entering energies as computed from the earth's magnetic field, and the sea level energies as computed from the entering energies and the coefficient of absorption.

The incorporation of (8) into the theory as represented by (6), leads to

$$\mu_e = \beta a E^{s-1} + \gamma/E$$

and

$$\mu_n = s\beta a E + s\gamma/E$$

This expression represents a  $\mu_n$  which increases with decrease of  $E$  for low values of  $E$ , but which decreases with decrease of  $E$  for high values of  $E$ .

A further remark must be made concerning the fact that in so far as there is a departure from the exponential law of absorption in the atmosphere, that departure is in the direction of a hardening of the rays as they approach the earth. At first sight this fact is contrary to the principle that the effective coefficient of absorption of the rays increases as the rays lose energy—a principle demanded by the asymmetry effect. The difficulty is only transitory, however; for, now, we introduce once more the idea of a wide range of primary energies entering the atmosphere, a hypothesis which is indeed required by the latitude and directional effects. Then, although each of these rays may *soften* as a result of its passage through the atmosphere, a suitably chosen energy distribution among the entering rays will insure that the measured radiation as a whole will harden with approach to sea level. The matter may be illustrated by considering the case of two distinct energies entering the atmosphere. Let the first, denoted by subscript unity, be the higher energy. For purposes of illustration we shall write, for some assigned direction,

$$n_1 = n_{10} e^{-\int \mu_1 dx}$$

This rather artificial looking expression is adopted because it corresponds to a coefficient of absorption, defined as  $-(1/n_1) (dn_1/dx)$  which is equal to  $\mu_1$  and is variable with  $x$ , if  $\mu_1$  varies with  $x$ .



In a similar manner, we write

$$n_2 = n_{20} e^{-\int \mu_2 dx}$$

The contribution of the two types of radiation is given by

$$n = n_1 + n_2 = n_{10} e^{-\int \mu_1 dx} + n_{20} e^{-\int \mu_2 dx}$$

The average coefficient of absorption of the combined radiation may be defined as  $\mu = -(1/n) (dn/dx)$ , so that

$$\mu = \frac{\mu_1 n_1 + \mu_2 n_2}{n_1 + n_2}$$

To illustrate the properties of this expression it will be sufficient to remark that if at  $x = 0$ , i. e., at entry to the atmosphere,  $n_1$  is small compared to  $n_2$ ,  $\mu$  approximates  $\mu_2$ . On the other hand at sufficiently large values of  $x$ , the quantity  $n_1$  is large compared with  $n_2$  on account of the required assumption that  $\mu_2$  shall be greater than  $\mu_1$ . Hence at large values of  $x$ , the coefficient  $\mu$  approximates  $\mu_1$ . Thus, under the condition cited we have an illustration of the fact that, while the individual quantities  $\mu_1$  and  $\mu_2$  both increase with  $x$ , the measured  $\mu$  decreases from  $\mu_2$  to  $\mu_1$ , with increase of  $x$ .

It is not my purpose to attempt to fix too definitely, at this stage, the exact forms of the details of the various elements of the corpuscular theory here presented. It will suffice to say that, within the general spirit of the ideas outlined in the elementary form of the theory, it is possible to make modifications which will include all the experimental facts concerned with absorption in the atmosphere, and with the latitude and directional effects. By the farther hypothesis already cited, and to the effect that in the case of heavy atom elements, frequency of shower production and the like depend upon a higher power of the primary energy than the first, we are able to correlate with theory the experiments already cited in relation to such phenomena, together with a number of other experiments relating shower production to altitude, and to the characteristics of the primary rays as determined by their direction, or by their behavior in the matter of asymmetry.

In the foregoing discussion we have taken as the measured intensity, the intensity determined by the secondaries. We may regard each primary as accompanied by a number of secondaries equal to the product of the number emitted per

centimeter of path and the range of the secondaries. It is this latter quantity which, in the foregoing theory, determines the contribution of a simple primary to the measured intensity. If the primary itself ionizes, the contribution in question should be increased by unity. This does not disturb the essentials of the theory, however.

It is of interest to note that if  $q$  is the number of secondaries produced per centimeter of path by a primary, and if each secondary has an energy of  $10^8$  electron volts, the loss of energy per centimeter of path would be  $q \times 10^8$ . On the other hand, the loss of energy per centimeter of path at a place where the primary energy is  $E$ , is, according to the elementary theory, equal to  $\mu E$ , where  $\mu$  is the absorption coefficient. Estimating all lengths in terms of centimeters of air compressed to the density of water, we have  $\mu = 0.005$ . Hence,  $q \times 10^8 = 0.005 E$ . If  $E$  is of the order  $10^{10}$  electron volts,  $q = 0.5$ . The range of  $10^8$  volt secondaries is of the order 20 cms in air compressed to the density of water. Hence the number of electrons accompanying each primary at the place where the primary energy is  $10^{10}$  volts is of the order  $20 \times 0.5 = 10$ . The question of whether the primary is, or is not, added becomes therefore of small importance; although the importance is increased for smaller primary energies.

Any difficulty concerned with the participation of the primaries in direct ionization may be removed by a modification of the theory in which what we have already regarded as the primaries are really photons in their journey through the atmosphere. We must suppose that these photons receive their energy and their directional characteristics in their creation from the real charged particle primaries by impact of the latter with the atoms of air in the higher regions of the atmosphere. If then we impute to the photons the same characteristics of shower production, energy loss, etc., as we have imputed to the primaries in the foregoing discussion, the whole theory already given follows again in all its essential details. As the photons lose energy their frequencies of course change.

*Possible Effects of Non-Ionizing Primaries:*—The question of whether the high-energy primaries do, or do not, ionize is one which has interesting significance in another connection. Many years ago I was lead to study it in connection with the replenishment of the earth's charge. Through the action of

the conductivity of the atmosphere, the earth is sending off its charge into space at such a rate that 90 per cent of the charge would disappear in 10 minutes, if there were no means of replenishing the loss. A whole class of theories to account for the replenishment invoke, in some form or other, the principle of an influx of high-energy electrons into the earth. In order to account for the continual replenishment it is necessary to assume that 1,500 electrons enter each square centimeter of the earth's surface per second. If these electrons ionized air at the normal rate characteristic of reasonably high-energy electrons, they would produce 60,000 ions per cc. per second, whereas in practice we find less than 10 ions per cc. per second. For this reason I sought a theoretical mechanism by which it might be possible to conclude that a charged particle of sufficiently high energy would fail to ionize. In terms of the classical theories of electrodynamics it was found possible, satisfactorily, to realize such a theoretical possibility. With the advent of the wave mechanics I sought some means by which such a situation could be evolved out of that form of theory also. It was found possible to introduce in a natural way an extension of the wave mechanical principles to permit of such a possibility, and recently this extension has been put out and published in detailed form. At my request Dr. Bramley has applied the modified wave mechanical theory to the problem of ionization so as to work out the preliminary details of the mathematical mechanism by which the ionization for high energies becomes suppressed.

More recently the possibility that very high energy particles might not ionize received a renewed interest from the fact that cloud chamber measurements apparently failed to reveal as many high-energy electrons as would be demanded by the magnetic effects, a fact which could be understood if the high-energy electrons failed to ionize. A further field of interest in the matter concerns recent experiments by J. Clay on the intensity of cosmic radiation at various depths below the surface of water. Fig. 3 represents Clay's results on measurements of the ionization produced in a closed vessel at various depths. The ordinates represent the ratio of the ionization to the ionization at sea level. The significant thing about these observations is the fact that with increasing depth, the ionization diminishes, but at 100 meters of water, the curve starts to flatten out and actually shows a rise at 250 meters,

falling finally to zero at about 270 meters. It is possible to understand this state of affairs if we invoke the idea that the primary agency is a charged particle which does not ionize directly, but only through the intermediary of secondaries, but which, as it loses its energy, comes finally to an energy at which it commences to ionize directly. In this range of energy, it has a short period of renewed activity, represented by the hump at 250 meters in Fig. 3; but this activity represents as it were the dying gasp of the ray; for, at this stage its energy has reached a value at which its subsequent path in water is limited to twenty or thirty meters, after which its active life is spent. The complete story of the matter is a little more complicated than is here implied<sup>8</sup> but the details serve to enhance more than to detract from the reasonableness of the explanation.

#### ORIGIN OF CHARGED PARTICLE ENERGY

The origin of charged particles of energies comparable with  $10^{10}$  volts presents, of course, an interesting field for speculation. If the particles come from the stars, it is reasonably certain that positives and negatives must be emitted in equal numbers; for, if not, a star would soon become charged to an enormous potential which would prevent further departure. Thus, if the sun emitted from its surface no more electrons per square centimeter per second than fall per square centimeter per second on the surface of the earth as electron cosmic rays, it would charge at the rate of about  $3 \times 10^{10}$  volts per year. Since both signs must be emitted equally in the steady state, it is obvious that neither sign of charge can receive its energy from a potential field originating in the emitting body; and symmetrical from all parts of that body; for a field which would promote the departure of one sign would prevent the departure of the other.

A whole galaxy of stars with but small charge on each could, in the aggregate, secure for the galaxy a potential of large amount.<sup>9</sup> Consider a galaxy of radius  $R$ , containing  $N$  stars, each of radius  $a$ , and charged to a potential  $V$  in relation to a point sensibly infinitely distant from itself but yet falling

<sup>8</sup>W. F. G. Swann, The Significance of J. Clay's Ionization Depth Data in Relation to the Nature of the Primary Cosmic Radiation, *Phys. Rev.* **46**, 432 (1934).

<sup>9</sup>W. F. G. Swann, "Methods of Acquisition of Cosmic Ray Energies," *Phys. Rev.* **42**, 914 (1932); also "Cosmic Rays," *The Military Engineer*, **26**, No. 146, 116-120, March-April, 1934.

within the galaxy. It can readily be shown that the potential at the surface of the galaxy is  $W = V_a N/R$ . If  $n$  is the number of stars per unit volume, this amounts to  $4\pi R^2 V_a n/3$ . This increases rapidly with  $R$  for fixed values of  $V$ ,  $a$ , and  $n$ , so that, for sufficiently large values of  $R$ ,  $W$  may be made large compared with  $V$  and we may secure a high potential difference between the body of the galaxy and intergalactic space by the assumption of a relatively small value of  $V$ . Unfortunately, when applied to the actual condition in the known galaxies, the possibilities of size are not sufficiently great to enable us to secure values of  $W$  even as great as  $V$ .

Apart from this, however, in such a charged galactic system, charged particles could dive through the galaxy, but particles of both signs could not enter. Such a situation, however, would lead us into difficulties of another kind, for, as I have shown elsewhere<sup>10</sup> if we had in the space between the stars a density of particles moving with the velocity of light and such as to correspond to a cosmic ray intensity equal to that observable upon the earth, they would, if of one sign, produce a space charge such as to give rise to differences of potential of the order of  $10^{18}$  volts between points in space separated by no more than one light year. At first sight one might think that this difficulty could be alleviated by the existence of a sort of space charge of low energy particles, of sign opposite to those of the high energy particles. However, so long as the resultant field is of the right kind to draw into the galaxy particles of one sign and produce high energy in them, it could not permit the entry of particles of the opposite sign unless they themselves had high energy before entering.

A possibility exists for the acquirement of high energies by charged particles without the invocation of large potential differences.<sup>11</sup> A change in magnetic field produces an electromotive force in any circuit through which the flux is changing. Now we know that sunspots are associated with magnetic fields and, therefore, it is easy to believe that such spots would exist on the stars. The magnetic field of a sunspot can grow to about 2,000 gauss in about 10 days. Without invoking the stellar spots themselves as origin of cosmic ray energies, I wish

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<sup>10</sup>W. F. G. Swann, "Space Density of Cosmic Ray Particles," *Phys. Rev.* **44**, 124, (1933).

<sup>11</sup>W. F. G. Swann, "A Mechanism of Acquirement of Cosmic-Ray Energies by Electrons," *Phys. Rev.* **43**, 217 (1933).

merely to use them as evidence of the existence of changing magnetic fields upon these stellar bodies. The practical fact then is that if, over the region of a star, we have an area whose diameter is comparable with fifty times the diameter of the earth, and in which a magnetic field is growing at a rate comparable with that at which it grows in a sunspot, then through the processes of electromagnetic induction, an electron would acquire an energy of  $10^{10}$  volts in one second, and before the field has grown to more than one-thousandth of a gauss.

I may cite another possibility of a more speculative nature, but possessing nevertheless certain advantages.<sup>12</sup> Many years ago, in order to provide an explanation of the earth's charge, of its magnetic field and several other matters, I proposed a modified scheme of electrodynamics. One of the consequences of this scheme was the prediction of a slow death of the positive charge in the case of a rotating body so that the surplus negative gradually accumulated until it built up a field in the atmosphere which insured that it passed away from the earth's surface at a constant rate such as would maintain equilibrium. If now, on the basis of this hypothesis we continue to trace the passage of electricity off into space, we see a growing volume distribution of electricity thinning out in density as we go outwards but continually increasing in total amount. This growing volume of electricity produces a difference of potential between the sphere and a point infinitely distant from it. If we allow the process to go on for an infinite time we find that the potential difference amounts to infinity, but the rate at which it mounts gets so slow as time goes on, that even astronomical times are not sufficient to result in more than differences of potential which, though large, are of an order of magnitude significant in cosmic ray phenomena. Thus if we should consider a star as large as the sun, with a surface density of current equal to that for the earth, we should find that in seventy years the potential difference between the star and infinity would have grown to about  $6 \times 10^9$  volts. In order for it to grow to six times this amount 70 million years would be necessary, so that, as I have remarked, even the invocation of astronomical time would not lead to potentials which were out of the realm of reason. As a matter of fact, the actual situation arising out of the physical mechanism which this example is designed to

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<sup>12</sup>W. F. G. Swann, "Cosmical Electrical Fields," *Phys. Rev.* 45, 295, (1934).

illustrate becomes complicated by various considerations involving the distances of the galactic systems from each other, the places of origin of cosmic rays, and so forth. All that I wish to emphasize is the possibilities inherent in a situation of this kind for the realization of potential differences of the order of magnitude comparable with those encountered in cosmic ray phenomena and such extrapolations into the regions of even higher energy as reason would permit.

Perhaps one of the easiest ways of accounting for the existence of high-energy particles is through the actions of phenomena analogous to thunderstorms in the stars. A thunderstorm is simply the result of the operation of a large electrical machine; and the fundamental principle of its operation is one in which positive and negative electrons are separated in amounts and through distances such as result in large difference of potential by using the tremendous forces of gravity acting on matter for the most part neutral. Even in the thunderstorm on earth, potential differences of the order of  $10^9$  volts can arise. An electron coming under the influence of the corresponding fields would become accelerated. Under suitable conditions, as C. T. R. Wilson has shown, it is possible for an electron to acquire energy in this way faster than it loses it to the surrounding gas. Moreover, the higher the energy of the electron, the less does it fritter away its energy. The electron is like a man who spends less and less as he acquires more and more wealth. Once the electron has surmounted its initial difficulties in getting started it can acquire energy equal to that determined by the potential differences available. Now, when we think of the enormous activities taking place in stars—particularly in novae, it would not be surprising if phenomena analogous to thunderstorms, or at any rate the essentials of an electrical machine, could exist on them such as would give rise to potential differences of the order of  $10^{10}$  volts, or more. One need not make the mistake of thinking that because a star is neutral as a whole there cannot exist on it a point which has a finite electrical potential in relation to infinity. For in a system composed, for example, of two adjacent spheres equally charged, one positively and the other negatively, there is between the positive charge and infinity a difference of potential comparable in fact with  $M/r^2$ , where  $M$  is the moment of the combined spheres, and  $r$  is half the distance between them.

In case we look to the stars as the source of cosmic radiation it is natural to suppose that our sun is not in a condition to be a contributor; for, if it were, it would be natural to suppose that it was the main contributor in view of its proximity, just as it is the main contributor of light. Finally, however, one must make a remark to the effect that even if the sun did contribute an appreciable amount of the cosmic radiation in the form of charged particles, it would not be so easy to detect the fact as might be supposed; for, in view of the complicated influence of the earth's magnetic field, the contributions from various parts of space would have very little relation to any special increase of intensity in the geometrical direction of the sun itself.

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#### Orientation in Science

The development and increasing popularity of orientation courses in science for college freshmen have created a need for textbooks to accompany such courses. This volume is the outcome of such a need. It is an attempt to give the student a rational and synoptic outlook upon man and the universe. The evaluation of this particular effort presents the reviewer with a difficult task. The book contains much meat, but it is largely hidden in a mass of generalities and platitudes. At times it seems doubtful whether the student will be able to take away any specific facts at all; then in places the book is clearly and succinctly written, only to bog down again in a morass of meandering and essentially meaningless phraseology. The physical sciences are treated in much better fashion than the biological sciences. A particularly good point is the binding and cohesive development of evolution (cosmic, geological and organic) as a great unifying technique. Conversely, a particularly bad point is the constant untiring use of italics and quotation marks. All desirable emphasis is lost by the over-use of these potentially valuable forms of accent. Opening the volume at random, a typical page contains 65 words in italics and 17 words in quotation marks. This is a positive detraction. The book may appeal to the philosophically-minded student, but is not conducive to clear thinking or concrete orientation on the part of the many. In the opinion of this reviewer, the book defeats its own purpose.—L. H. S.

**The Backgrounds and Foundations of Modern Science**, by Richard E. Lee. xxv+536 pp. Baltimore, the Williams and Wilkins Co. 1935.

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#### The Origin of the Solar System

For those who have become "universe-conscious" as a result of the writings of Jeans, Eddington and the rest, this well-written volume will provide the next step in adventures in cosmic thinking. It is a clear, stimulating account of the properties and workings of the sun, the planets, the satellites, the asteroids, the comets and the meteors. In technical difficulty it is a good step above the strictly popular volumes, but it is so clearly and directly written that the step is an easy one, and well worth the taking. The book represents the Page-Barbour Foundation Lectures given at the University of Virginia in 1934. The first two sections on the dynamical and physico-chemical properties of the solar system lead up to the important and thought-provoking third section, which discusses in detail the postulated theories of the origin of the system. Recent new and little-known data are presented, and the author's own hypothesis of origin is elaborated. After an hour or two of letting one's fancy roam afar in space and time, one ceases to worry about the expected letter that is three days overdue.—L. H. S.

**The Solar System and its Origin**, by Henry Norris Russell. 141 pp. New York, the Macmillan Co. 1935.